MODIFICATION OF THE PROTO-II ACCELERATOR POWER FLOW FOR MULTI-PURPOSE USE

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Abstract

PROTO-II is a nominal 10 TW, 320 kJ accelerator which has been used to study imploding plasma physics for the last few years. The machine has been modified to make it useful as a bremsstrahlung radiation source and to lower the inductance for better energy coupling to gas puff loads. The triplate water transmission line has been converted to a 4-line horizontal 8-plate transformer section feeding a 4-layer insulator stack, using a multiple rod crossover network. Hinged plates allow a constant impedance transmission line for gas puff applications and make a 2:1 impedance transformer for bremsstrahlung applications. For Gas Puff operation, vertical MITLs connect the 4-layer stack to the load. For bremsstrahlung operation, conical MITL plates connect each of the four lines to feed one side of a 2-cathode ring electron beam diode. Circuit simulations of the power flow predict up to 270 kJ of energy at 1.0 MV into the Gas Puff diode and up to 230 kJ at 1.5 MV into the electron beam diode. Accelerator performance under the new configuration is discussed.

Introduction

The PROTO-II modification project encompasses design, construction, and installation of hardware which converts the previous horizontal triplate output lines to a horizontal four-line configuration used to drive a four-layer water/vacuum insulator. The vacuum region interior to the insulator stack accommodates both gas puff and electron-bremsstrahlung diode loads and the short magnetically insulated transmission lines (MITLs) required to make the electrical connections.

The composite schematic diagram in Figure 1 shows three parts of the machine modifications. The crossover network accomplishes the transition from two output lines (the triplate) to four output lines. The transformer section joins the four output lines to the insulator stack and can be configured either as a matched system (1/8 Ω) to drive imploding gas puff loads or as a 2:1 step-up transformer (1/4 Ω) to drive an electron beam diode. The insulator stacks separate the water lines from the vacuum line/load portions of the accelerator. The upper half of the diagram depicts the electron-bremsstrahlung (BREMS) configuration with an insulator stack 1/3 taller than that used for the gas puff (PUFF) configuration depicted in the lower half of Fig. 1. The increased stack height is necessary to accomodate the higher voltage for BREMS (1.6 MV, compared to 1.2 MV for PUFF).

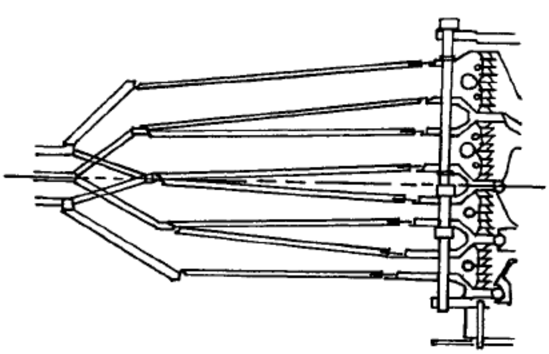

Figure 1. Schematic diagram of PROTO-II modifications.

The design of the power flow in the water section and the insulator stack is presented in this paper. Details of the vacuum region portions of the hardware (vertical MITLs convoluting to a disk for PUFF and conical MITLS feeding a concentric double-cathode-ring BREMS diode) will not be presented. The remainder of the paper is divided into four sections which discuss the crossover network, the transformer section, the insulator stack, and results of the initial PUFF power flow tests completed in the last few weeks. Installation of the BREMS MITLs and diode is underway concurrent with this meeting.

Crossover Network

Description

The crossover network provides a transition from the two existing 16-segment PROTO-II output lines to the four output lines which connect to the insulator stack. The design concept was taken from the Sandia DEMON crossover [1] which uses an array of crossed rods to accomplish crossover of power flow between two plates. The PROTO-II crossover differs from the DEMON configuration in that angled plates are used to connect the top and bottom ground plates of the 2-line output to those of the 4-line transformer. This results in an electrically "closed" configuration which eliminates any losses due to external stray capacitances. We used the DEMON data base to design more conservative electric field levels in the PROTO-II crossover. We also built a full scale model of one crossover section with input and output lines and measured both the transmitted waveshapes and TDR signals to check for inductance surprises and to define a circuit model for circuit calculations using the SCEPTRE computer program. Details of the water tank model and calculations are presented in the accompanying paper.

Electrical Design

Table 1 gives the electrical stress parameters for two designs which used 1.9-cm-diameter crossover

TABLE 1. CROSSOVER ELECTRICAL STRESS ESTIMATES

Rod spacing	5.1 cm	7.6 cm
Peak Field (kV/cm)$^{(1)}$	470-476	317-328
F^+_{AWRE} (kV/cm)$^{(2)}$	442	446
Mean Field (kV/cm)	315	175
Point-plane streamer$^{(3)}$ transit time t_{eff}	47 ns	138 ns

Notes: (1) Ranges represent two different ways of calculating peak field.

(2) F^+_{AWRE} is the "breakdown" field estimated from $0.23\alpha t_{eff}^{-1/3} A^{-.058}$ (MV/cm), with $\alpha = 1 + 0.12(E_{max}/E_{mean} - 1)^{1/2}$, t_{eff}(μsec) = 60 ns, A = 700 cm^2.

(3) From $Ft_{eff}^{1/2} = 0.0685$ for positive streamer transit without delay.

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14. ABSTRACT
PROTO-II is a nominal 10 TW, 320 kJ accelerator which has been used to study imploding plasma physics for the last few years. The machine has been modified to make it useful as a bremsstrahlung radiation source and to lower the inductance for better energy coupling to gas puff loads. The triplate water transmission line has been converted to a 4-line horizontal 8-plate transformer section feeding a 4-layer insulator stack, using a multiple rod crossover network. Hinged plates allow a constant impedance transmission line for gas puff applications and make a 2:1 impedance transformer for bremsstrahlung applications. For Gas Puff operation, vertical MITLs connect the 4-layer stack to the load. For bremsstrahlung operation, conical MITL plates connect each of the four lines to feed one side of a 2-cathode ring electron beam diode. Circuit simulations of the power flow predict up to 270 kJ of energy at 1.0 MV into the Gas Puff diode and up to 230 kJ at 1 .5 MV into the electron beam diode. Accelerator performance under the new configuration is discussed.

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rods at 1.0 MV. The final design used a spacing of 7.0 cm, resulting in four rods per PROTO-II line sector. These estimated stresses are lower than the values obtained on DEMON, which appears to successfully operate above both breakdown and streamer transit criteria. It is possible that a delay in streamer formation time does not allow sufficient time for closure during the DEMON pulse. The PROTO-II design is more conservative, and initial results show successful operation without water breakdown.

Transformer Section

Description

The transformer is located between the crossover network and the insulator stacks. It is designed to be operated either as a matched (1/8 Ω) array of four parallel transmission lines to drive PUFF, or as a parallel 4-line 1/8 Ω to 1/4 Ω step-up transformer to drive BREMS. The transformer section is formed from eight trapezoidal aluminum panels which are connected to hinges at the output end of the crossover. Sixteen sets of eight such plates fill the sixteen sectors or PROTO-II. At the inner radius of the hinged plates, adjustable plates contact the metal insulator stack endplates and allow for the slight length difference between PUFF and BREMS, plus a small additional tolerance. The contact plates rest on steps machined into the the insulator stack endplates. No special current contact provisions are necessary. The steps in the endplates are arranged to allow sequential foldup of all eight transformer plates to provide easy access to the water side of the insulator stack.

Electrical Design

The transformer input impedance (1/2 Ω for each of the four lines) was set by specifying an 11.5 cm plate spacing at the attachment point to the crossover. This spacing gives an input impedance in water of 6.67 d/R = 0.51 ohm ± 8% per line, or a 0.128 ohm system impedance.

The transformer output impedances were set by positioning of the metal insulator stack endplates on which the hinged transformer plates rest. For PUFF, the insulator stack endplates form short 5-cm-spacing transmission lines from the transformer connection point (at R varying from 68.6 cm to 77.2 cm) inward to the start of the water flare region at R = 59.4 cm. This sets the output impedance per line at 0.46 ohms ± 7%. At the start of the water flare, the impedances are equal to 0.56 ohms per line. The 5 cm spacing was selected because of previous Sandia experience on PROTO-II and from a high voltage experiment on the MITE testbed [2].

For the BREMS option, the addition of two insulators and gradient rings of the same height to each individual insulator stack "automatically" opens the final transmission line spacings to 10.08 cm. This spacing gives a mean output inpedance per line of 0.92 ohms ± 7% at the transformer connection points and 1.13 ohms at the start of the water flare.

Insulator Stacks

Description

The insulator stacks for both PUFF and BREMS are designed to operate up to 1.2 MV and 1.6 MV, respectively. The insulator stack endplates extend into the water region and have stepped edges to accept the hinged transformer plates, as explained earlier. The inner surfaces of the endplates interface to the vacuum region MITLs.

For PUFF, the MITLs make use of a concept first proposed by I. Smith [3] for electron beam applications and applied to this situation by D. McDaniel and I. Smith. Twelve anode and twelve cathode vertical MITLs are attached to the insulator stack endplates via four inflatable firehose current contact gaskets and are convoluted into a single disk feed, placing all of the external inductance in parallel.

For BREMS, MITL cones with gravity-held contacts rest on the insulator stack endplates. The four output lines feed a concentric, double cathode diode, with each line feeding one side of a cathode ring. The drop-in gravity-contact design was chosen to provide faster turn-around in the BREMS mode. Inner and outer cathode rings are electrically isolated by a ground-plane MITL electrode which connects to the anode.

The PUFF and BREMS insulator stacks are designed with many common parts. Change between PUFF and BREMS tubes involves adding two flat-backed insulators and two secondary flux-excluder gradient rings, changing the center flux-excluder ring, and replacing the tie rods with longer ones. The tube tie rod arrangement allows for subassembly of individual tube units and removal of one to four of the units at a time for stack repairs.

Electrical Design

The electrical design considered fields in the water flare, stage-to-stage grading uniformity, average longitudinal field stress, cathode-end triple-point fields, and vacuum flare design.

Figures 2 and 3 show the overall grading of certain single PUFF and BREMS tube units.

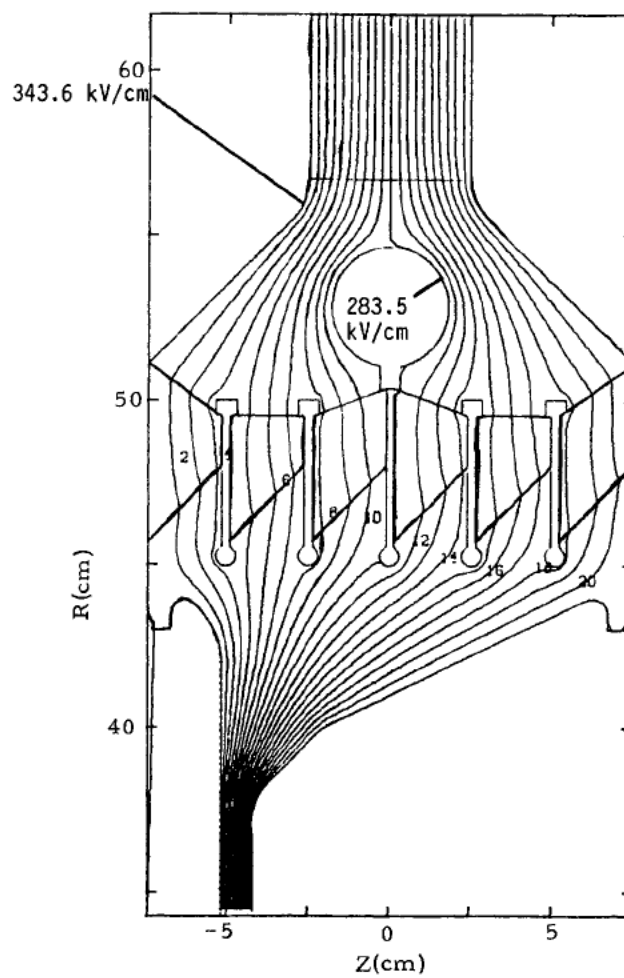

Figure 2. PUFF tube grading and water flare fields (assuming 1200 kV on tube)

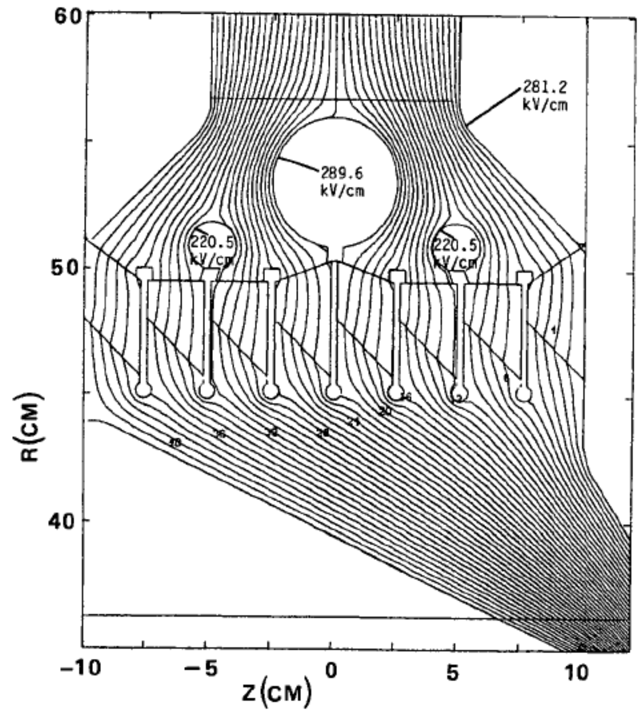

Figure 3. BREMS tube grading and water flare fields (assuming 1600 kV on tube)

Peak electric fields in the water flare section are tabulated in Table 2 and compared to the estimated breakdown thresholds.

TABLE 2. Water Flare Electric Fields

	Flux Excluder		Flare Corner	
Tube	Peak Field (kV/cm)	Breakdown Fraction	Peak Field (kV/cm)	Breakdown Fraction
PUFF	284	72%	344	87%
BREMS	290	74%	281	71%

Note: Breakdown fraction assumes breakdown field F^{+}_{AWRE} = 394 kV/cm (see Table 1), assuming t_{eff}= 60 ns and the area (1000 cm^2) taken as that stressed to ≥ 90% of peak field for all four tubes.

Stage-to-stage grading of the insulator stack was designed to be uniform to within ± 2% by iterating the insulator angle and flux excluder geometry with JASON computer calculations.

For the PUFF vacuum flare region (1.2 MV insulator stack voltage), the electric field on the negative electrode is held below 300 kV/cm until the electrode becomes flat, to avoid kinetic losses from electron emission lifting off from convex sections of the electrode and crossing the gap to the positive electrode. The design features well-trapped electron flow along the MITLs. Also to inhibit electron emission, gradient-ring-tip fields are designed to be below 300 kV/cm (275 kV/cm maximum). The cathode triple-point fields were designed to be less than 35 kV/cm ($E_{||}$). Similar requirements were designed into the BREMS configuration.

The estimated insulator-vacuum interface flashover fields are tabulated in Table 3, using

$$F = 175\ t_{eff}^{-1/6} A^{-1/10}\ \text{(kV/cm)}$$

with t_{eff}= 60 ns and areas corresponding to a single tube and the set of four.

TABLE 3. Estimated Flashover Fields

	Single Tube		Set of Four	
	A (cm^2)	F (kV/cm)	A (cm^2)	F (kV/cm)
PUFF	5.0×10^3	119	2.18×10^4	103
BREMS	7.3×10^3	115	2.90×10^4	101

Both PUFF (at 1.2 MV) and BREMS (at 1.6 MV) are stressed to E ~ 90 kV/cm. This corresponds to operation at ~ 78% of the flashover field for a single tube and ~ 89% for the set of four.

Predictions and Results

Circuit Simulations

SCEPTRE computer simulations have been run to predict the electrical performance of PROTO-II after the modifications for both configurations.

For BREMS, the calculations included the water section, insulator stack, vacuum section, and a bipolar Child-Langmuir diode impedance model with a constant electrode plasma closure velocity of 7×10^6 cm/sec. The area covered by the double-cathode-ring diode was taken to be 200 cm^2. The energy delivered to the electron beam load under various conditions was between 180-230 kJ at 1.33-1.5 MV with a pulse width of 45 ns (FWHM).

Corresponding calculations for PUFF gave up to 270 kJ into the diode at 1.2 MV.

Experimental Results

The machine modifications ran very smoothly due to extensive pre-assembly and fitting before installation. The gas puff vacuum MITLs and diode were installed for a brief testing period before the bremsstrahlung hardware arrived. Two shots have been taken at full marx charge into a shorted load. In both shots, the water and vacuum feeds performed flawlessly. We measured 8.5-9.0 MA delivered past the vacuum interface at peak voltages of 1.2-1.4 MV and peak powers of 8.0-9.5 TW. The measured inductance of the diode was 4.7 nH (calculated inductance was 4.8 nH). These represent significant improvements over the corresponding values (4.0 MA, 1.2 MV, and 5-6 TW, with a 7 nH shorted diode inductance) before the modifications.

The BREMS configuration is now being installed on PROTO-II and testing will continue in this mode until the end of July.

References

[1] B. N. Turman, personal communication.

[2] W. Hsing, R. Mattis, and D. McDaniel, personal communication.

[3] I. D. Smith, Proceedings of the International Conference on Electron Beam Research and Technology, Vol. I, p.472, Albuquerque, New Mexico, November 1975.

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